

ENGINEERING SERVICES FOR THE NEXT GENERATION NUCLEAR PLANT (NGNP) WITH HYDROGEN PRODUCTION

Test Plan – Intermediate Heat Exchanger PCHE Type

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ACRONYMS

ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
CTF	Component Test Facility
DDN	Design Data Need
DOE	U.S. Department of Energy
FSV	Fort Saint Vrain
GA	General Atomics
GT-MHR	Gas Turbine Modular Helium Reactor
HTGR	High-Temperature, Gas-Cooled Reactor
HTTR	High Temperature Test Reactor
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
NGNP	Next Generation Nuclear Plant
MHR	Modular Helium Reactor
MHTGR	Modular HTGR
NP-MHTGR	New Production Modular HTGR
ORNL	Oak Ridge National Laboratory
PCHE	Printed Circuit Heat Exchanger
TRL	Technology Readiness Level

1 INTRODUCTION

1.1 Purpose

This Test Plan provides a high-level description of a technology development program to support design, fabrication, and deployment of a helium-to-helium intermediate heat exchanger (IHX) for the Next Generation Nuclear Plant (NGNP). Startup of the NGNP is currently scheduled for 2021. The described activities are those that are seen at this time as necessary to advance the Technology Readiness Level (TRL) of the IHX from its current level to the level required prior to hot startup of the NGNP.

This Test Plan is applicable to an IHX for the plant configuration shown in Figure 1, which General Atomics (GA) has selected as the reference NGNP configuration for the NGNP technology development roadmapping effort under which this Test Plan has been prepared. This configuration is essentially the same as the preferred configuration that GA selected for the NGNP during the Phase A Conceptual Design Studies in early 2008 (GA Report 911120), except that the reactor outlet temperature has been increased from 900°C to 950°C to be consistent with the high-level NGNP Project requirement that the reactor be designed not to preclude operation at 950°C. As shown in Figure 1, the IHX required for this NGNP configuration has a heat transfer duty of only 65 MWt.

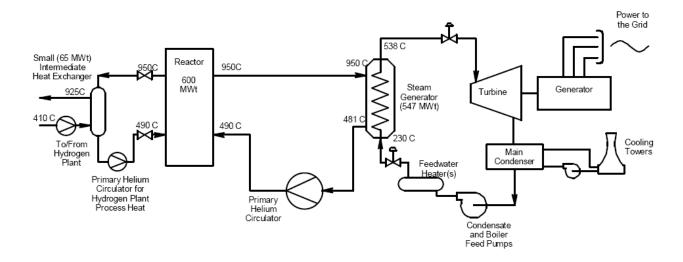


Figure 1. NGNP Configuration for Technology Development Roadmapping

It is important to note that a decision was made recently by the NGNP Project to reduce the nominal reactor outlet helium temperature for the NGNP from 950°C into the range of 750°C to

800°C. This decision was based on the conclusion that the primary interest of potential end users of gas-cooled reactor technology at this time is cogeneration of electricity and process steam. GA believes that the reduced reactor outlet helium temperature eliminates the need for an IHX in the NGNP design because the outlet gas temperature will not be high enough to support efficient operation of hydrogen plants based on the advanced hydrogen production processes that are currently under consideration (e.g., S-I thermochemical process and high-temperature electrolysis. Thus, GA plans to eliminate the heat transport loop that supplies process heat to the hydrogen production plants from its reference NGNP design. Nevertheless, because the current technology development road mapping task was started and largely completed while the reactor outlet helium temperature objective for NGNP was still 950°C, the effort to prepare this Test Plan describing the technology development activities required for the IHX in Figure 1 continued.

Because the NGNP design process is at a very early stage, the design details needed to precisely define testing requirements are currently largely unavailable. Consequently, this Test Plan is intended primarily to identify the testing activities that are likely to be needed and to provide cost and schedule estimates, which are necessarily based on engineering judgment. It is assumed that this Test Plan will be updated periodically as the NGNP design progresses and that detailed test plans and test procedures will be prepared by the testing organizations for the specific tests that are actually conducted.

1.2 Scope

An initial TRL of 2 has been assigned to the IHX because the technology required to build an integrated IHX of the size required for NGNP is not judged to be sufficiently mature to warrant a TRL rating of 3 (proof of concept). This Test Plan provides a high-level description of a technology development program to advance the TRL of the IHX from 2 to 8, which is the level that must be achieved prior to hot startup of the NGNP. Section 2 lists applicable reference documents. Sections 3 through 8 describe the technology maturation activities for a given TRL step (i.e., 2 to 3, 3 to 4, etc.). Section 9 provides an integrated schedule for IHX technology development and a summary of the estimated costs.

1.3 Background

1.3.1 IHX Description

The IHX is a high temperature gas-to-gas heat exchanger that transfers thermal energy from the NGNP primary coolant to a secondary loop. It is subject to temperatures of up to 950°C on the primary side and temperatures 25°C to 50°C lower on the secondary side. The pressure is 7 MPa on the primary side and 7.1 MPa on the secondary side. GA has selected helium to be the working fluid in the secondary loop. The NGNP IHX will have a heat transfer duty of 65 MWt in

GA's preferred NGNP configuration, but could have a heat transfer duty of up to about 600 MWt in other possible NGNP configurations. It is assumed that the IHX will be a compact printed-circuit type heat exchanger (PCHE) comprised of a number of identical PCHE modules. The PCHE modules are fabricated by etching channels into metal plates and diffusion bonding the plates together. These modules along with the connecting ducting, headers, supports, etc. comprise the heat transfer subsystem, which is enclosed within a pressure vessel. The vessel and heat transfer internals comprise the IHX system.

1.3.2 Status of IHX Technology Development

PCHE technology has been developed and commercially deployed by Heatric Corp, but for non-nuclear applications, and there has been no demonstration of a PCHE of the size required for the NGNP or in the expected operating conditions of the NGNP. For NGNP, the PCHE module and other internal components must be fabricated from a material that has adequate creep and fatigue strength at 950°C and is resistant to deleterious aging in a high-temperature impure helium environment.

The NGNP Technology Development Program has identified Alloy 617 as the preferred material for the PCHE and Haynes 230 as a potential backup material. However, the high cobalt content (i.e., 10 to 15%) of Alloy 617 has been a concern to GA. Specifically, erosion of cobalt-containing surface scales that may form as a result of reactions between Alloy 617 and impurities in the helium may result in entrainment of Co particulates in the primary coolant. Activation of these particulates in the reactor core would result in a high level of radioactivity in the primary coolant loop. However, recent measurements by INL of the cobalt content of the surface scale that formed on Alloy-617 samples aged in an oxidizing impure helium environment revealed that the cobalt content of the surface scale was only about 0.2%. So as long as the helium coolant chemistry supports the formation of a stable oxide film on the Alloy 617, cobalt entrainment in the primary coolant should not be a significant problem.

The Heatric Corp is currently conducting a PCHE development program for Alloy 617. Heatric has recently reported success in fabricating diffusion bonded specimens that meet Alloy 617 strength requirements and in fabricating a demonstration PCHE module that meets Heatric's leakage requirements. Unfortunately, Heatric is very secretive about its PCHE design and fabrication processes, so development of design rules within the ASME code for a compact heat exchanger based on Heatric PCHE technology may not be possible.

It is planned to use LWR reactor steel (SA508/SA533) for the NGNP IHX vessel, and sufficient insulation will be needed to keep vessel temperatures below ASME code limits. The design of the NGNP IHX vessel thermal barrier is expected to be similar to the IHX vessel thermal barrier design for the HTTR IHX in Japan. Operation of the HTTR IHX with a helium inlet temperature of 950°C has been demonstrated. However, the NGNP IHX vessel thermal barrier will still have

to be tested to verify its performance and durability within the expected NGNP operating environment. Based on the demonstration of IHX vessel thermal barrier technology in the HTTR, the technology maturity of the vessel is considered to be at least TRL 4, so the TRL of the vessel is not limiting with respect to the overall technology readiness of the IHX.

In spite of the above-noted progress in demonstrating the availability of a suitable material (Alloy 617) for the IHX, an initial TRL of 2 is assigned to the IHX because the technology required to build an integrated IHX of the size required for NGNP is not judged to be sufficiently mature to warrant a TRL rating of 3 (proof of concept). Also, additional environmental aging and thermal cycling testing of Alloy 617 may be needed to more-conclusively prove that there is minimal potential to introduce cobalt into the primary helium coolant under all realistic operating conditions for the NGNP.

1.3.3 NGNP High-Temperature Materials R&D Program

Table 6 of [INEEL/EXT-05-00758] provides a list of potential candidate materials for the intermediate heat exchanger (IHX) and other NGNP high-temperature components; however, only a few of these are considered to be viable due to a lack of materials property data or ASME code acceptance. Based on creep resistance above 850°C, the leading candidates for such applications are Alloy 617 and Haynes 230. (Hastelloy XR, which was developed by the Japanese for use in the HTTR IHX, is another possibility.) However, neither Alloy 617 nor Haynes 230 is currently in Section III Class 1, 2 and 3 or the high-temperature NH subsection of the ASME Code. They are both approved up to 982°C in Section VIII Div 1, but the allowable stress levels are quite low at 900°C and 950°C.

Since its inception, the NGNP materials R&D Program has concentrated on Alloy 617 because it is the most mature with respect to data availability, has superior creep resistance at the high end of the anticipated NGNP temperature range (950°C), and is considered to be the closest to gaining ASME code approval in Section III. According to [INEEL/EXT-05-00758], the NGNP R&D Program also plans to include testing of Haynes 230 and Hastelloy XR, but acknowledges that given the multiplicity of alloys, joining conditions, and creep-fatigue test conditions, it will be necessary to eventually make a down selection to limit the testing to a reasonably manageable effort. [INL/EXT-06-11750] discusses the results from a program to study the microstructure and mechanical properties of Alloy 617 and Haynes 230 aged in air at temperatures up to 1000°C. These aging effects tests were carried out on two commercial heats of Alloy 617 and one heat of Haynes 230.

Recently, an IHX Materials Research and Development Plan [INL PLN-2804] was issued. This plan outlines an extensive R&D program that is designed to acquire the data needed for an ASME code case for Alloy 617.

2 APPLICABLE DOCUMENTS

Table 1. Documents Applicable to IHX Technology Development

Document Number	Title	Date
ANL/EXT-06/46	Preliminary Issues Associated with the Next Generation Nuclear Plant Intermediate Heat Exchanger Design, ANL Nuclear Engineering Division,	September 2006
INEEL/EXT-05-00758	Next Generation Nuclear Plant Materials Research and Development Program Plan	September 2005
INL/EXT-06-11750	Summary of Studies of Aging and Environmental Effects on Inconel 617 and Haynes 230	September 2006
INL PLN-2804	Next Generation Nuclear Plant Intermediate Heat Exchanger Materials Research and Development Plan, April 2008	September 2006
GA Report 911107/0	NGNP and Hydrogen Production Preconceptual Design Studies Report	July 2007
GA Report 911119/0	NGNP IHX and Secondary Heat Transport Loop Alternatives Study	April 2008
GA Report 911120/0	NGNP Steam Generator Alternatives Study	April 2008
GA Report 911125/0	NGNP Composites R&D Technical Issues Study	October 2008

3 TEST PLAN TO ADVANCE FROM TRL 2 TO TRL 3

A TRL of 3 is achieved when proof-of-concept is established. This requires that sufficient industrial experience or testing at laboratory scale provide proof of viability in the anticipated service. The following activities are required to advance the TRL of the IHX from 2 to 3. These include:

- 1. Perform computer modeling to develop an IHX conceptual design.
- 2. Perform testing to determine environmental aging and thermal aging and cycling effects on Alloy 617 at elevated temperatures in an impure helium environment representative of that anticipated in the NGNP.
- 3. Verify PCHE fabrication processes (e.g., diffusion bonding and chemical etching) for the selected material (presumably Alloy 617)

These activities are discussed in the following sections. An overall schedule and cost estimate summary is provided in Section 9.

3.1 Develop IHX Conceptual Design

Preliminary conceptual designs of a number of PCHE-type compact IHX variations developed by GA NGNP team member Toshiba have been presented in GA Reports 911107 and 911119. However, additional work is needed to further develop the design, including more detailed thermal and structural analyses to confirm that the design will meet performance and lifetime requirements under transient conditions as well as normal operating conditions. It is assumed that Toshiba, with support from GA, will continue to take the lead in designing the IHX for the GA NGNP team. This activity will start early in conceptual design and will require about 6 months to complete. The cost is estimated to be about \$150K.

3.2 Environmental Aging and Thermal Aging Effects Testing

3.2.1 Test Objective

Perform environmental aging and thermal aging and cycling tests to verify that the expected NGNP operating environment will not have a materially adverse effect on the high-temperature materials being considered for the IHX. As discussed in Section 1.3.2, Alloy-617 is the leading candidate, so the testing will be focused on this material. Other candidate materials include Haynes 230 and Hastelloy XR. It is anticipated that testing of these materials will proceed only in the unexpected event that Alloy-617 is determined to be unsuitable (perhaps due to its high cobalt content).

3.2.2 Test Description

Recently, an IHX Materials Research and Development Plan (INL PLN-2804) was issued. This plan outlines an extensive R&D program that is designed to acquire the data needed for an ASME code case for Alloy 617. The plan covers the environmental aging and thermal aging effects testing that is required and it is assumed that the testing would be conducted in accordance with this plan.

3.2.3 Test Conditions

Test conditions must be representative of the expected IHX service conditions and shall be as identified in PLN-2804. The primary helium coolant design impurity levels shown in Table 2 (from GA Report 911125) are applicable to both the MHTGR and GT-MHR. The expected impurity levels are applicable to the GT-MHR. The design impurity levels are considerably higher than the levels that would be expected during equilibrium operating conditions. Once the NGNP design is better defined, analyses will be needed to confirm that the design helium coolant impurity levels in Table 2 are applicable to the NGNP and to estimate the expected impurity levels specific to the NGNP design and operating conditions.

Table 2. Design and Expected Levels of Primary Coolant Impurities

Impurity	Design Value	Expected Value*	Units
H ₂ O	2.0	0.5	ppmV
CO ₂	2.0	1.0	ppmV
СО	5.0	2.0	ppmV
H ₂	10.0	3.0	ppmV
CH₄	2.0	0.1	ppmV
N_2	10.0	2.0	ppmV
Particulates	10.0	1.0	lb/yr
* For GT-MHR operatin	g at 100% power v	vith Tin = 490°C ar	nd Tout = 850°C

3.2.4 Test Configuration

Most of the various mechanical properties (e.g., stress-rupture, relaxation strength, tensile properties, creep-fatigue, etc.) tests will be performed on standard test specimens using standard laboratory equipment. These tests will be performed in accordance with ASTM standard procedures. Long-term testing (e.g., creep, thermal aging, crack growth, etc.) will need to be performed in a dedicated Long Term Aging Facility.

3.2.5 Required Data

Details of the testing proposed by INL to support development of an ASME code for Alloy 617 are provided in Appendix A of PLN-2804. Section 8 of PLN-2804 provides a summary of the testing program. Data is specifically needed to conclusively demonstrate Alloy-617, if used as the material of construction for the IHX, will not be a source of significant circulating cobalt contamination in the primary coolant loop.

3.2.6 Test Location

The tests to determine the effects of helium impurities on high-temperature materials at reactor operating temperatures should be performed at INL and/or ORNL using the laboratory-scale helium flow test facilities that were specifically constructed to support the NGNP Program. The mechanical properties measurements can be performed at INL and/or ORNL or at any of a number of commercial testing laboratories.

Two commercial laboratories that have extensive capability to perform stress-rupture and creep testing over a range of temperatures in accordance with ASTM standard methods include:

IMR Test Labs

Portland, Oregon 503-653-2904

E-mail contact: Bob Adrian at bob@khametal.com

Westmoreland Mechanical Testing & Research, Inc.

Youngstown, Ohio 724-537-3131

E-mail contact: admin@wmtr.com

Depending on the number of samples to be tested, it may be necessary to perform tests at both of the National Laboratories and at a number of commercial testing facilities to complete the tests in a reasonable time frame. Long-term creep-rupture tests (if performed) will need to be performed in a dedicated Long Term Aging Facility. Long-term thermal aging would also best be conducted in a dedicated Long Term Aging Facility. It is assumed that this facility would most likely be located at ORNL.

3.2.7 Data Requirements

Quality assurance must be in accordance with experimental data or validation testing for non-safety-related components. Further, all work performed to support the NGNP R&D Program must be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776. This program invokes the national consensus standard ASME

NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.2.8 Test Evaluation Criteria

The conditions for successful completion of the high-temperature material properties testing are (1) the required data as identified in Section 3.2.5 has been obtained, (2) the data satisfies the data quality requirements as defined in Section 3.2.7, and (3) the data shows that Alloy-617, if used as the material of construction for the IHX, will not be a source of significant circulating cobalt contamination in the primary coolant loop.

3.2.9 Test Deliverables

The deliverables include:

- Test specification
- Test plan
- Test procedure
- Test report

The final test report shall include:

- Discussion of test method
- Equipment employed
- Equipment calibration verification
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

3.2.10 Schedule and Cost

This activity will start early in conceptual design and is estimated to cost about \$1M. The duration is estimated at about 18 months, but this is greatly depending on the thermal and environmental aging protocols that are used.

3.3 Verify PCHE Fabrication Processes

This activity involves verification of the PCHE fabrication processes (e.g., diffusion bonding and chemical etching) for Alloy 617. The Heatric Corp is currently conducting a PCHE development program for Alloy 617. Heatric has recently reported success in fabricating diffusion bonded

specimens that meet Alloy 617 strength requirements and in fabricating a demonstration PCHE module that meets Heatric's leakage requirements. However, Heatric is very secretive about its PCHE design and fabrication processes, so development of ASME code design rules for a compact heat exchanger based on Heatric PCHE technology may not be possible. Consequently, it may be necessary for the NGNP Project to evaluate IHX fabrication techniques such as diffusion bonding on its own. This additional R&D area is addressed in Section 8.2 of PLN-2804.

This activity will start early in conceptual design based on the assumption that Alloy-617 will be shown to be a suitable material for the IHX application. GA has roughly estimated the duration of the task to be one year and the cost to be about \$200K.

4 TEST PLAN TO ADVANCE FROM TRL 3 TO TRL 4

Successful completion of the IHX design and fabrication methods development activities and materials testing outlined in Section 3 will establish proof-of concept (TRL of 3). A TRL of 4 is achieved when technical feasibility and functionality has been verified at bench-scale. For the IHX, a TRL of 4 will be achieved by constructing a bench-scale PCHE module from the selected material and performing tests to confirm that the PCHE module meets design requirements.

4.1 Test Objective

Build and test a bench-scale PCHE module to verify that leak-tightness requirements can be met and to determine the temperature distribution in the PCHE. Use the measured temperature distribution to verify analytical model predictions.

4.2 Test Description

Test a bench-scale PCHE module and perform flow testing to ascertain leak tightness and to measure the temperature distribution within the module. Pumping high temperature air through the primary side of the PCHE and pumping low temperature air through the secondary side will provide the conditions needed for the test. Compare the test results to the temperature distribution predicted by computer modeling.

4.3 Test Conditions

High-pressure/high temperature air at 950°C will be supplied to one side of the PCHE. The other side will be provided with high-pressure/low-temperature air at 200°C.

4.4 Test Configuration

The test configuration will consist of a bench-scale PCHE module, a source of hot air (950°C), a source of cold air (200°C), and instrumentation. The hot-air and cold-air sources will include a heater, a compressor, and the necessary ducting to deliver the air to the PCHE.

4.5 Required Data

The following measurements are required:

- Hot air inlet and outlet temperature
- Hot air inlet and outlet pressure
- Hot air inlet and outlet mass flow rate. Any difference between the inlet and outlet flow rates will indicate PCHE leakage.
- Cold air inlet and outlet temperature
- Cold air inlet and outlet pressure

- Cold air inlet and outlet mass flow rate. Any difference between the inlet and outlet flow rates will indicate PCHE leakage.
- PCHE surface temperatures at several locations to be determined)

4.6 Test Location

The PCHE manufacturer's facility

4.7 Data Requirements

Quality assurance must be in accordance with experimental data or validation testing per non-safety-related components. Further, all work performed to support the NGNP R&D Program must be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776. This program invokes the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

4.8 Test Deliverables

The deliverables include:

- Test specification
- Test plan
- Test procedure
- Test report

The final test report shall include:

- Discussion of test method
- Equipment employed
- Equipment calibration verification
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

4.9 Costs and Schedule

The estimated cost to construct and test the bench-scale PCHE module is \$1M. The estimated duration of this activity is about one year. The schedule is shown in Figure 2 in Section 9.

5 TEST PLAN TO ADVANCE FROM TRL 4 TO TRL 5

A TRL of 4 is achieved upon successful bench-scale testing of a PCHE module as outlined in Section 3. A TRL of 5 is achieved when IHX components have been demonstrated at experimental scale in a relevant environment. The following activities are required to advance the TRL from 4 to 5:

- 1. Construct an experimental-scale model of the vessel and perform tests to verify the thermal barrier design
- 2. Perform materials properties testing on specimen obtained from the PCHE module that was built and tested to advance the TRL from 3 to 4 (see Section 4)

5.1 Experimental-Scale Testing of IHX Vessel

5.1.1 Test Objective

The vessel material has been designated to be SA-508/SA533. SA508/533 low-alloy steel (forgings and plate, respectively) is approved under Section III of the ASME Boiler and Pressure Vessel code for use in nuclear components. The maximum temperature limit permitted by Subsection NB for Class 1 components is 371°C. Therefore it is imperative that the vessel thermal barrier perform its required function under all possible operating conditions. This series of tests will be used to determine the response of the IHX vessel and its thermal barrier to thermal cycling, mechanical vibrations, acoustic loading, and flow and thermal gradients.

5.1.2 Test Description

A series of tests that duplicate the possible range of the IHX vessel and its thermal barrier's operational conditions will be performed on an engineering-scale model of the vessel assembly. These tests will include thermal cycling, mechanical vibrations, acoustic loading and flow and thermal gradients. These tests are summarized as follows:

- The thermal cycling and thermal gradient and flow gradient tests can be done at the same time. While maintaining the environment on the outside of the vessel at expected "exterior conditions" the helium inside the vessel can be thermal and flow cycled from the lowest expected temperature and flow level to the highest expected temperature and level and back again at a rate which duplicates the maximum expected transient rates. This cycling will result in the thermal gradients across the vessel system and thermal cycling of the components. This test must be performed at the expect pressure range.
- Expected mechanical vibrations can be imposed on the vessel assembly to evaluate its response to this input.

• Expected acoustic loading can be imposed on the vessel assembly to evaluate its response to this input.

5.1.3 Test Conditions

The required test conditions will be specified in the Test Specification to be prepared for this test. In general, this test must be performed using helium at the design operating temperatures and pressure levels. The helium flow rate must simulate operating conditions.

5.1.4 Test Configuration

The vessel/thermal barrier testing will be performed on an experimental-size version of the IHX vessel. The test rig will be designed based on the test requirements specified in the Test Specification and will be described in the Test Plan. Both the Test Specification and Test Plan will be prepared as the initial steps of the test program. The test facility must include a means of heating and pressurizing helium to the required temperature and blowing that helium through the test rig. Provisions must be made to duplicate design conditions both inside and outside the vessel.

5.1.5 Required Data

The following measurements are required for the vessel/thermal barrier test:

- Hot helium inlet and outlet temperature
- Hot helium inlet and outlet pressure
- Hot helium inlet and outlet mass flow rate
- Helium velocities
- Vessel temperatures
- Acoustic levels
- Vibrations

5.1.6 Test Location

It is likely that the IHX vessel/thermal barrier testing will be conducted at the IHX vendor's facility. However, the testing could also be performed at any of a number of commercial testing facilities. One such facility is Wyle Laboratories. Another is Hazen Research. Information for Wyle Laboratories and Hazen Research is provided below.

Wyle Laboratories
128 Maryland St.
El Segundo, Ca 90245
(310) 563-6662
john.shimada@wylelabs.com

Wyle Laboratories is headquartered in El Segundo, Calif. and employs approximately 4,200 employees at more than 40 facilities nationwide. Wyle is one of the nation's leading providers of specialized engineering, scientific, and technical services to the Department of Defense, NASA, and a variety of commercial customers. Wyle has been designing and building unique test fixtures, equipment and entire test facilities for industry and government use for more than 50 years. These facilities include centrifugal and linear accelerators, vibration systems with up to six axes of motion, high intensity acoustic chambers, dynamic shock devices like crash barriers, plus rail dynamics test facilities and numerous combined-environment test systems. In the nuclear sector, Wyle has qualified more equipment than anyone else in the industry.

Hazen Research Inc 4601 Indiana Street Golden, Colorado 80403 Phone: (303) 279 4501

www.hazenusa.com

Hazen services include laboratory-scale research on new processes or adaptation of known technology to new situations, followed by pilot plant demonstration, preliminary engineering, and cost analysis. Projects range from beaker-scale experiments, material testing and analyses to multimillion-dollar continuous pilot or demonstration plants. Activities began at the present location in Golden, Colorado, in 1961 and the staff has since grown to over 120. Sixteen buildings containing an extensive inventory of laboratory and process equipment provide the flexibility for evaluating different unit operations.

5.1.7 Data Requirements

Quality assurance must be in accordance with experimental data or validation testing per non-safety-related components. Further, all work performed to support the NGNP R&D Program must be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776. This program invokes the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

5.1.8 Test Evaluation Criteria

The conditions for successful completion of the experimental-scale IHX testing are (1) the required data as identified in Section 5.1.5 has been obtained, (2) the data satisfies the data quality requirements as defined in Section 5.1.7, and (3) the test data show that the response of the IHX vessel and its thermal barrier to thermal cycling, mechanical vibrations, acoustic loading, and flow and thermal gradients meets design requirements.

5.1.9 Test Deliverables

The deliverables include:

- Test specification
- Test plan
- Test procedure
- Test report

The final test report shall include:

- Discussion of test method
- Equipment employed
- Equipment calibration verification
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

5.1.10 Cost and Schedule

The estimated cost to construct and test the experimental-scale IHX vessel is \$2M. The estimated duration of this activity is two years. The schedule is shown in Figure 2 in Section 9.

5.2 Materials Properties Testing on PCHE Module

It is anticipated that the PCHE module will be fabricated using a diffusion bonding process and that other joining techniques such as welding will be used to assemble the PCHE modules with other IHX internals (e.g., module supports, ducting, etc.). The PCHE material may experience some degradation of its mechanical properties as a result of these joining processes. Mechanical properties testing of the joints will be needed to identify acceptable joining parameters such as temperature, applied pressure, and hold times. The testing should include measurements of the tensile, creep, creep-fatigue, and fatigue properties of the joints.

It is assumed here that the IHX vendor will provide diffusion-bonded samples for the required testing and that these samples will be obtained from the bench-scale PCHE module that was constructed and tested to advance from TRL 3 to 4. Samples of weldments joining the PCHE module with other IHX internals will also be needed for testing, and it is assumed that these will also be provided by the IHX vendor. In fact, heat exchanger vendors such as Heatric are likely already performing such testing, but it is unknown if they will make the data available (or provide samples for testing by others) to support development of ASME design rules for a compact IHX.

Consequently, development of the ASME code rules may be problematic and it may be necessary for the NGNP Project to design, fabricate, and test prototypical specimens on its own.

5.2.1 Test Objective

Perform mechanical properties testing of Alloy-617 diffusion-bonded joints to identify joining parameters such as temperature, applied pressure, and hold times that do not result in significant degradation of the mechanical properties of the base material. Similarly, test weldments that are representative of the joining processes used to assemble the PCHE modules with other IHX internals.

5.2.2 Test Description

Recently, an IHX Materials Research and Development Plan (INL PLN-2804) was issued. This plan outlines an extensive R&D program that is designed to acquire the data needed for an ASME code case for Alloy 617. The plan covers the required testing, and it is assumed that the testing would be conducted in accordance with this plan. The testing will include measurements of the tensile, creep, creep-fatigue, and fatigue properties of the diffusion-bonded joints and weldments.

5.2.3 Test Conditions

Test conditions must be representative of the expected IHX service conditions and shall be as identified in PLN-2804.

5.2.4 Test Configuration

Most of the various mechanical properties (e.g., stress-rupture, relaxation strength, tensile properties, creep-fatigue, etc.) tests will be performed on the test specimens using standard laboratory equipment. Any long-term testing that may be required (e.g., creep, thermal aging, crack growth, etc.) will need to be performed in a dedicated Long Term Aging Facility.

5.2.5 Required Data

Details of the testing proposed by INL to support development of an ASME code for Alloy 617 are provided in Appendix A of PLN-2804. Section 8 of PLN-2804 provides a summary of the testing program. The testing will include measurements of the tensile, creep, creep-fatigue, and fatigue properties of diffusion-bonded joints and weldments.

5.2.6 Test Location

The mechanical properties measurements can be performed at INL and/or ORNL or at any of a number of commercial testing laboratories, including those identified in Section 3.2.6.

5.2.7 Data Requirements

Quality assurance must be in accordance with experimental data or validation testing for non-safety-related components. Further, all work performed to support the NGNP R&D Program must be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776. This program invokes the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

5.2.8 Test Evaluation Criteria

The conditions for successful completion of the mechanical properties testing are (1) the required data as identified in Section 5.2.5 has been obtained, (2) the data satisfies the data quality requirements as defined in Section 5.2.7, and (3) the data shows that the techniques used to fabricate the PCHE module do not significantly degrade the mechanical properties of the Alloy-617 base material.

5.2.9 Test Deliverables

The deliverables include:

- Test specification
- Test plan
- Test procedure
- Test report

The final test report shall include:

- Discussion of test method
- Equipment employed

- Equipment calibration verification
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

5.2.10 Schedule and Cost

The cost and schedule for this activity is highly uncertain given the questions associated with IHX vendor support of ASME code activities. The authors have estimated the cost of the testing to be about \$4M and the duration to be 18 months, but acknowledge that these estimates could be considerably in error. The schedule is shown in Figure 2 in Section 9.

It should also be noted that the material properties testing outlined in Section 3.2 combined with the testing described in this section essentially comprises the entirety of the IHX materials R&D Plan in PLN-2804. The estimated total cost of the mechanical properties testing defined in PLN-2804 is given as \$6.4M (in Table 35 of PLN-2804) and the total cost of the R&D Program, including equipment purchases, Quality Assurance, Program Management, etc., is given as \$23.6M (in Table 36 of PLN-2804).

6 TEST PLAN TO ADVANCE FROM TRL 5 TO TRL 6

TRL 5 is achieved when the PCHE module design and fabrication processes and the IHX thermal barrier design have been verified by testing. A TRL of 6 is achieved when the IHX components have been integrated into a subsystem and demonstrated at pilot scale in a relevant environment.

The TRL of the IHX will be advanced from 5 to 6 by performing design and computer performing modeling to size and configure the IHX heat transfer subsystem and overall IHX to meet all operational requirements. All analyses will be performed by GA, a GA NGNP team member (Toshiba), or a designated subcontractor using computer codes that have been verified and validated in accordance with the applicable requirements of ASME NQA-1.

The estimated cost of this design activity is \$150K and the estimated duration is 6 months. The schedule is shown in Figure 2 in Section 9.

7 TEST PLAN TO ADVANCE FROM TRL 6 TO TRL 7

To achieve a TRL rating of 7, the assembly must complete integrated engineering-scale demonstration in a relevant environment. For the IHX, a TRL of 7 is achieved by the following activities:

- 1. Perform testing on engineering-scale mock-ups to obtain critical information required for final design and to verify key features of the design.
- 2. Finalize the IHX design and prepare and issue the procurement specifications for the prototype IHX

7.1 Design Support Testing

7.1.1 Test Objective

Perform testing on engineering-scale mockups to verify critical design features of the IHX.

7.1.2 Test Description

The required testing will be design specific and will be determined during IHX preliminary design. However, it is anticipated that the following testing will be needed based on the Toshiba provided information presented in GA Report 911119.

- Perform testing to confirm the predicted thermal and hydraulic characteristics, including heat transfer, vessel temperatures, and overall IHX system pressure losses
- Confirm by experiment the flow distribution throughout the IHX (both primary and secondary inlets and outlets) accompanied by analytical evaluation.
- Perform testing to obtain data on the frequency spectra and sound pressure levels that may be generated by the IHX as a function of flow velocities
- Perform testing to determine the physical and operational characteristics of insulation relative to thermal cycling, mechanical and acoustic vibrations, and the effects of flow and thermal gradients.
- Various sliding seals, expansion joints, and other seals are expected in the IHX design for installation and replacement purposes. Perform testing to obtain the data needed to confirm the design feasibility, measure leak rates under operating conditions, and measure the influence of various factors on seal performance.
- Perform testing to obtain the data needed to accurately determine the flow-induced vibration characteristics around the IHX and its associated piping. The flow induced excitation mechanisms of concern are turbulent buffeting, vortex shedding and fluid elastic instability.

7.1.3 Test Conditions

The required test conditions for each of the engineering-scale design support/validation tests will be specified in the Test Specification prepared specifically for the test. It is considered likely that most testing will need to be performed with flowing helium at NGNP design temperatures and pressure levels.

7.1.4 Test Configuration

The test rig for each test will be designed based on the test requirements specified in the Test Specification, and will be described in the Test Plan. The test facility must include a means of heating and pressurizing helium to the required temperature and blowing that helium through the test rig.

7.1.5 Required Data

The required data for each test will be specified in the Test Specification for the test.

7.1.6 Test Location

Given that most, if not all, of the tests will need to be performed with flowing helium at NGNP design temperatures and pressure, the best location for these tests would be the INL Component Test Facility (CTF), assuming that it has been built and is available. However, the tests could also potentially be performed at the IHX vendor's facility or at a commercial testing facility. One such facility is Wyle Laboratories (see Section 5.1.6).

7.1.7 Data Requirements

Quality assurance must be in accordance with experimental data or validation testing per non-safety-related components. Further, all work performed to support the NGNP R&D Program must be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776. This program invokes the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

7.1.8 Test Evaluation Criteria

The test evaluation criteria for each test will be defined in the detailed Test Plan that will be prepared for the test. In general, a test is successfully completed when the data requirements and test objectives as specified in the Test Specification have been met.

7.1.9 Test Deliverables

The deliverables for each design support/verification test include:

- Test specification
- Test plan
- Test procedure
- Test report

The final test report shall include:

- Discussion of test method
- Equipment employed
- Equipment calibration verification
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

7.1.10 Cost and Schedule

The required testing will be design specific and will be determined during IHX preliminary design; consequently, any cost and schedule estimates provided at this time are only guesses. However, based on the potential tests identified in 7.1.2, the authors have estimated a cost of \$10M and duration of three years. The schedule is shown in Figure 2 in Section 9.

7.2 Finalize IHX Design and Prepare Procurement Specifications

This activity will include a thorough evaluation of the design with respect to the test results for the design support/verification tests. Modifications to the IHX design and/or the IHX performance models will be made as necessary based on the test results. The procurement specifications for the NGNP IHX will be prepared and issued upon completion of the final design. The design work and analyses will be performed by GA, a GA NGNP team member, or a designated subcontractor using computer codes that have been verified and validated in accordance with the applicable requirements of ASME NQA-1. The procurement specifications will be prepared and issued in accordance with the QA Program requirements applicable to procurement control.

The estimated cost of this activity is \$1M and the estimated duration is 15 months. The schedule is shown in Figure 2 in Section 9.

8 TEST PLAN TO ADVANCE FROM TRL 7 TO TRL 8

A TRL of 8 is achieved by demonstrating an integrated prototype of the system in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. A TRL of 8 will be achieved for the IHX by testing a full-size prototype IHX in the INL CTF under conditions that are the same as the NGNP operational environment.

8.1 Testing of Full-Size IHX in the INL CTF

8.1.1 Test Objective

Testing will be performed to confirm the performance of the full-size NGNP IHX under NGNP normal operating conditions and anticipated transients. The objective of the testing is to very the following performance characteristics of the IHX:

- Heat Transfer
- Vessel temperature
- System pressure losses
- Leak tightness
- Acoustic response
- Flow induced vibrations

8.1.2 Test Description

The full-size (65 MWt) NGNP IHX will be subject to testing in the INL CTF under conditions that are the same as the NGNP operational environment. The testing of the full-size IHX will be performed to confirm the performance of the IHX under NGNP normal operating conditions and anticipated transients.

8.1.3 Test Conditions

The required test conditions will be specified in the Test Specification prepared specifically for this test. Testing will be performed to characterize IHX performance under NGNP conditions for normal operation and anticipated transients.

8.1.4 Test Configuration

The testing will be performed in the INL CTF. The test configuration will be defined in the Test Plan specifically prepared for this test.

8.1.5 Required Data

The following measurements are required for the tests:

- Helium flow rates
- Helium inlet and outlet pressure
- Helium inlet and outlet temperatures
- Acoustic measurements
- Vibration measurements
- Component temperatures

8.1.6 Test Location

INL Component Test Facility

8.1.7 Data Requirements

Quality assurance must be in accordance with experimental data or validation testing per non-safety-related components. Further, all work performed to support the NGNP R&D Program must be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776. This program invokes the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

8.1.8 Test Evaluation Criteria

The test evaluation criteria will be defined in the detailed Test Plan that will be prepared for the test.

8.1.9 Test Deliverables

The test deliverables include:

- Test specification
- Test plan
- Test procedure
- Test report

The final test report shall include:

- Discussion of test method
- Equipment employed
- Equipment calibration verification
- Original test data
- Summarized and reduced test data

• A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

8.1.10 Cost and Schedule

The estimated cost is \$5M. The estimated duration of the test is one year. The schedule is shown in Figure 2 in Section 9.

9 COST AND SCHEDULE SUMMARY

Figure 3 provides an integrated schedule for IHX technology development and design and a summary of the estimated costs.

		Estimated						Calendar Year	r Year					
TRL	Activity	Cost (\$K)	2009 2	2010 2011	1 2012	2 2013	3 2014	4 2015	5 2016	16 2017	7 2018	3 2019	2020	2021
	NGNP Schedule													
	Common Conceptual Design		I											
	Common Preliminary Design		-		-	_								
	NHSS Conceptual and Prelim. Design		1	-		-								
	Final Design						ļ	ļ	4	1		ļ		
	Site Work and Construction							4	4	4		ļ		
	Startup and Testing											•		
	IHX Design, Fab, & Installation Schedule													
	Conceptual Design			I										
	Preliminary Design					_								
	Final Design						\parallel	\parallel	\parallel					
	Prepare and issue IHX procurement documents									+				
	Fabricate prototype IHX									I	4			
	Install IHX in NGNP											I	_	
	IHX Technology Development													
2→3	Modelling to confirm IHX feasibility	150	I											
	Environmental aging and thermal cycling testing on Alloy 617	1000		_										
	Verify diffusion bonding and chemical etching processes	200												
3→4	Construct and test bench-scale PCHE module	1000	•	+										
4→5	Mechanical properties and environmental testing of samples from bench-scale PCHE module	4000		<u> </u>	+	_								
	IHX vessel design and experimental-scale testing	2000		4		-								
9~9	Computer modeling to complete IHX preliminary design	150				1								
2←9	Design support testing on engineering-scale mockup(s)	10000					ļ	Ļ	T					
	Finalize IHX design and issue procurement specs	1000								+				
2→8	Construct prototype IHX									I	+			
	Test prototype IHX in NGNP operating environment	2000				_					l	4		
	Total	24500												

Figure 2. Schedule and Cost Estimate Summary for NGNP IHX Development

